Tuning nonlinear metamaterials with light

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Abstract

We introduce a novel approach for creating tunable electromagnetic metamaterials. We demonstrate experimentally that magnetic resonance of a split-ring resonator (”meta-atom” of a composite material) with a photodiode and a varactor diode can be tuned by changing the intensity of an external light source. Moreover, for two coupled resonators we show that we can achieve light-induced switching between dark and bright modes. We study experimentally dynamic tunability and self-induced nonlinearity of the light-tunable ”meta-atoms”, and also demonstrate a light-controllable magnetic reflector array based on tunable split-ring resonators.

1. Introduction

The interest towards the study of tunable, nonlinear and active metamaterials has seen dramatic growth within recent years [1]-[4]. Various efforts are being made towards achieving tunable metamaterials, either by externall influence [2] or by employing their nonlinear response [3]. At microwave frequencies, a split-ring resonator (SRR) loaded with a varactor diode represents one of the simplest tunable nonlinear meta-atoms. A biased regime of varactor diode operation was proposed in Ref. [4] and it allows significant tuning of the resonance. At the same time this approach may not be practical for applications in bulk structures due to the required circuitry.

In this work we propose a conceptually novel design of light-tunable metamaterials, in which every element or meta-atom can be independently controlled. Using the standard printed circuit board technology we realize such meta-atoms as SRRs loaded with varactor diodes, whose biasing is supplied locally by photodiodes integrated into the same element. The photodiodes operating in the photovoltaic mode produce a bias voltage that depends on local illumination which, in turn, affects the capacitance of the varactors and the resonant frequency of the SRR. Thus, we demonstrate that SRRs magnetic resonance can be tuned by changing the intensity of an external light source. We employ coupled SRRs to demonstrate enhancement of the resonant response and switching between the bright and dark modes of the coupled pair of resonators. We perform nonlinear measurements to investigate dynamic tunability and self-induced nonlinearity of the proposed light-tunable SRR. To demonstrate further effects we design light-controllable magnetic reflector array based on tunable SRRs and demonstrate its unique functionality for reflection, shaping, and focusing of electromagnetic waves.

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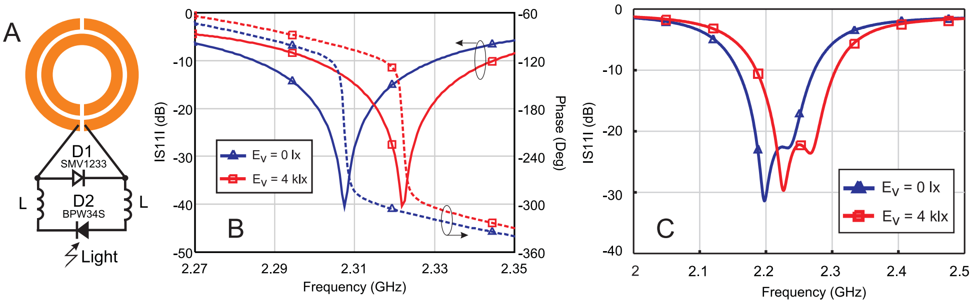

Fig. 1: (A) Schematic of the light-tunable SRR. (B) Measured magnitude and phase of the tunable SRR reflection coefficient for an external light with two values of illuminance E_v.

2. Results

First we investigate a single light-tunable SRR (Fig. 1(A)). We use SRRs identical to those described in Ref. [5]. To achieve tunability we solder a varactor diode (SMV1233, Skyworks$^{\mathrm{TM}}$) in additional gap in the outer ring of the SRR. The bias voltage for the varactor diode is produced by a photodiode (BPW-34-S, Opto Semiconductors$^{\mathrm{TM}}$) that operates in the photovoltaic mode. The biasing circuit is rf-blocked by chip inductors. We measure the magnetic response of the fabricated SRR with a symmetric microstrip loop antenna. From the measurements of the reflection coefficient we observe a shift in the resonant frequency of the SRR when the light intensity illuminating the photodiode increases from 0 lx to 4 klx (Fig. 1(B)).

Next we demonstrate that the sensitivity of the studied meta-atoms to the external light may be also increased by considering structures composed of several coupled resonators. We consider the case of two coupled SRRs placed in parallel planes with their axis coinciding. In our work we fine-tune the coupling and, the splitting of the resonant frequencies in the pair of SRRs without light is such that it is equal to the shift in the resonant frequency of an isolated SRR when the intensity of light is changed. As a result, in such structure by changing the light intensity it becomes possible to switch between the bright and dark modes for the fixed frequency of the electromagnetic wave (Fig. 1(C)). We change the orientation of the photodiode in the SRR (to provide forward voltage on the varactor diode) and study self-induced nonlinearity of the structure. We observe an increase in the resonant frequency of the SRR when the applied power increases. At the same time, increasing of the light intensity causes a decrease of the SRR's resonant frequency. Thus, we have a competition between two effects and get an additional degree of freedom to control the properties of the SRR. The bistable behaviour of the SRR can be clearly seen in the Fig. 2.

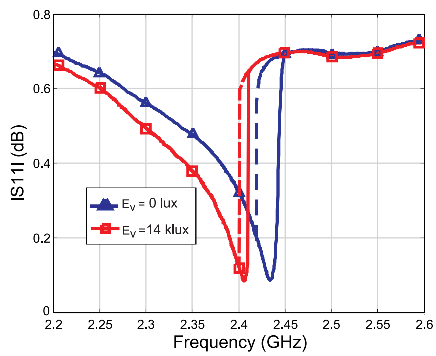

Fig. 2: Measured reflection coefficient of the light-tunable SRR showing multivalued behaviour for 19 dBm input power for different values of illuminance E_v: (solid line) forward sweep and (dashed line) reverse sweep.

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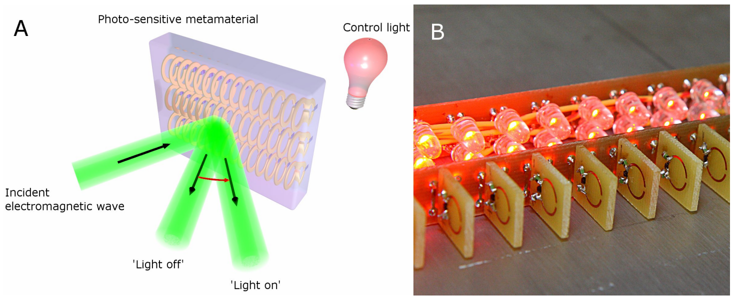

Fig. 3: (A) Operational principle of a photo-sensitive metamatrial. (B) The photograph of the light-controllable magnetic reflector array based on light-tunable SRRs, and a light source for illumination.

Next, we study the magnetic reflector formed by an array of 24 broadside-coupled SRRs placed close to a metallic screen (see Fig. 3 (B)). Each ring of such SRR contains a varactor diode whose biasing is provided by a pair of photodiodes. By illuminating the array with light of varying intensity, we are able to change the properties of the structure inhomogeneously. Thus, by changing the applied light pattern, the properties of the metamaterials can vary in such a way that, e.g., the electromagnetic wave incident on the metamaterial experiences a locally varying phase shift and reflects at different angles (see Fig. 3 (A)). The magnetic reflector array is experimentally investigated in a parallel-plate waveguide. We demonstrate experimentally an efficient control over the angle of the reflected beam by changing the illuminating light pattern. We are able to achieve beam steering of approximately 12 degrees. We also show that it is possible to switch between focusing and defocusing regimes for the reflected beam by moving the maximum of illumination from centre to the edges of the reflector structure.

3. Conclusion

We have suggested and experimentally demonstrated a novel approach to metamaterial tunability. We have fabricated SRRs loaded with varactors and photodiodes, and demonstrated a shift of the magnetic resonance due to a chance of the illumination intensity. We have employed several approaches of collective SRR response to enhance this tunability, and also designed light-controllable magnetic reflector array which allows steering, focusing or defocusing of the reflected beam depending on the illumination pattern. We believe this approach is useful for creating bulk metamaterials which properties can be controlled by reconfigurable light sources.

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